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# Time Dependent Monte Carlo (TDMC) Simulation Data Output for Photon-Tissue Interactions

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**Abstract**: Time dependent (TD) Monte Carlo (TDMC) photon-tissue interactions simulation program code generated photon fluencies (Joule/cm²) for ten picosecond (ps) time series [100 , 200, … 1000] for Continuous Wave (CW) laser source. TD MC ANSI Standard C program code "trmc.c" was modified and compiled to generate photon fluence distributions inside the imaging tissue model. Cylindrical coordinate system was chosen to compile the ANSI standard C based photon walk program code. Radial r, and depth z axis created cylindrical mesh grid (r, z) array. Collimated isotropic point laser source within a semi-infinite homogeneous medium was used. Radial diameter of cylindrical coordinate system 2r = 6.0 cm, depth z = 3.0 cm. In this study, TD analysis of CW MC photon fluencies for the photon-tissue interactions simulation mesh grid geometry for Nz = 30, and Nr = 30 dimensions within 3 cm x 6 cm was performed. In the MC simulation program code, the tissue absorption and scattering coefficients were chosen as $\mu_a$ = 0, and $\mu_s$ = 100 $cm^{-1}$. 60.000 photons were sent into the tissue from (x, y, z) = (3.0, 3.0, 3.0) cm isotropic laser source position. The values of photon fluencies are varying depend on the time in tissue environment were recorded in the ANSI standard C program data output file. The time intervals were chosen by 100 picosecond (ps) steps, from 100 ps to 1000 ps sequentially. Depend on the increasing time steps, CW photon migration was observed inside the tissue, successfully. TD analysis of CW photon fluencies will be used when making the time resolved diffuse optic tomography (TRDOT) device. Forward model problem weight matrix will be built based on the TD distributions of MC photon fluencies, then photon fluencies will be used in the inverse problem solution image reconstruction algorithm. The location of buried inclusions will be determined.

**Keywords:** Time resolved (TR) Monte Carlo (MC) simulation photon fluencies, Continuous Wave light

## Introduction

Monte Carlo (MC) simulation of time-resolved (TR) photon fluencies for continuous wave (CW) light was run. Photon fluence distributions were generated according to the MC simulation program code photon walk steps. Collimated isotropic point laser source was selected according to the radial coordinate system, which was written and used earlier in academy [1] (Steven L. Jacques' s ANSI standard C program trmc.c). Photons propagated in semi-infinite tissue geometry model. Photon fluence distributions were saved for 10 different time intervals from 100 to 1000 ps, respectively. Academic society is dividing the photon migration search into three different groups, which are Continuous Wave (CW), Time Resolved (TR) or Time Gated (TG), and Frequency Domain (FD) based on the diffuse optic tomography (DOT) device instrumentation concept. They usually request to use specifically defined laser wavelength such as a low power laser for their instruments. Different time interval mode analyses of CW and TR photon propagation run mode cannot be analyzed in the same spot, since while TR mode of CW mode uses different time intervals for CW laser (photon fluencies increase in entire tissue imaging geometry), on the other hand TR run mode uses ps or fs laser pulse (photon fluence withers away for one specific voxel by the time). For TR analysis of CW photon migration, it is possible to see increasing photon fluencies in all over the tissue geometry structure by ongoing time intervals. The instrumentation engineers and researchers would benefit to use generated photon fluencies when they are using mathematical inverse problem solution algorithms. This work covers new TD based view of existing CW photon propagation run mode. On the other hand, the traditionally used time mode is TR or TG run principle. In that mode, short,

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narrow band full width half maximum (FWHM) ps or fs laser pulse is sent inside the tissue. From the detector point, escaping laser photons were collected by single photon avalanche diode (SDAD) photodetectors, or fast scientific streak cameras such as intensified CMOS or CCD imagers. Rapid superficial photons come first, then deep penetrating photons come later to the detector point.

**Time Dependent Continuous Wave Diffuse Light (TDCWDL)**

Time dependent continuous wave diffuse light (TDCWDL) search is the philosophical approach for scientists who concern for following to get advantages from photon-tissue interactions and photon migration for low energy biomedical optic imaging applications. This research field involves time dependent mode, time resolved, or time gated analysis of penetrating photons. Photon migration research comprises of time resolved (TR), continuous wave (CW), or frequency domain (FD) run modes used for diffuse optic tomography (DOT) biomedical optic imaging modality. In practice, low-power (< 20 milliwatt) semiconductor lasers are used for photon generation, un-polarized collimated incident gaussian laser beam photons are sent through imaging tissue. Time Resolved Diffuse Optical Tomography (TRDOT) devices are using narrow band full width half maximum (FWHM) laser pulses in the order of picosecond (ps) or femtosecond (fs) [2]. TR run mode DOT devices are one derivative of CW lasers, which are using ps pulse FWHM, since the photon propagation in average fat tissue is in the order of 100 ps. If an observer has detector measurement system, which it makes the photons visible such as in yz intersection, depend on the tissue absorption ($\mu_a$) and scattering ($\mu_s$) tissue optic parameters, photon penetration depth inside the imaging tissue is varying [2]. TRDOT and CWDOT devices are used to investigate optical properties of the biological tissue [3-6]. Using TRDOT device instrumentation has depth analyses advantages over CWDOT systems, since it makes possible to guess depth dependent analyze by increasing different time gates. Researchers are using the Time Gated (TG) or Time Resolved (TR) analyze methods for this purpose. Image reconstruction phase has two different experimental measurements to be done, which one is with inclusion and the other one is with non-inclusion experiment setups. Dividing two different experimental measurement data is giving the perturbation data, which then used to reconstruct the inclusions inside the imaging experimental tissue media. From the device instrumentation view, TRDOT imaging modality has some advantages over the CWDOT imaging modality, since it makes possible to group time gated analyze which then can be used in depth dependent image reconstruction algorithms, successfully. Photon propagations between different time gates can be connected to the relative depth for imaging tissue. For this simulation study, different time gates were used which starts from 100 ps to 1000 ps. For the maximum photon depth penetration, photons at time 200 ps can go deeper than the photons at 100 ps time interval, clearly. There are actually two common known scientific research approaches to guess the distributions of penetrated photons inside the imaging biological tissue. The other most known and applied method is the theoretical physics diffusion equation approach. Light penetration inside the tissue model can be illustrated by time dependent or independent CW diffusion equation (DE) model, successfully. In this work, time dependent (TD) Monte Carlo (MC) simulation model was used. In MC simulations photon can be regarded as a particle. Escaping photons are counted from tissue surface. Escaping photons are collected depend on the source-detector distance (SDS) and tissue optical parameters such as absorption ($\mu_a$), scattering ($\mu_s$) and anisotropy coefficient ($g=\langle\cos\Theta\rangle$), respectively. Diffuse optical tomography (DOT) modality has two basic structures which first one is defining the forward model problem and the second one is using mathematical inverse problem solution algorithms. Setting up forward problem model is the definition of physical problem. This is about how photon migrations behave in specific imaging tissue model. Second one is the using successful mathematical inverse problem solution algorithms. In the image reconstruction or mathematical inverse problem solution algorithm, forward problem model is used. In the general form, forward problem model is represented by matrix format, since second derivative of DE is reduced to first order then it becomes single matrix multiplication. As a result, forward problem model constitutes the photon trajectory weights, in other word, photon fluence multiplications in the equation system for under each source and detector positions in imager device which has multi source and detector fiber optic probes with photodetectors, CMOS or CCD imagers. Theoretical physics DE or MC simulation methods are both for constructing the forward problem model weight matrix functions, which constitute the photon weight functions for under each source and detector locations in specific tissue imaging geometry model. By applying the mathematical inverse problem solution algorithm, the inclusions inside the imaging medium can be solved and illustrated by selecting the appropriate image reconstruction algorithms. By modeling the photon propagation, photon trajectories can be guessed. Usually the photon trajectories are more likely to banana shape between each source and detector positions for back-reflected tissue geometric model approach. There might be three different geometrical physical positioning for DOT devices; these are transmission through, back reflected, and cylindrical approaches. Depend on the required application field in medical clinics; appropriate device geometry can be selected for better data acquisition. For example, cylindrical source-detector placements are usually chosen for better image contrast for breast tumor imaging; but for some

other imaging applications back-reflected geometry can be used. In the next section, between source and detector positions, forward problem model photon weight trajectory is illustrated in **Fig. 1**.

### Forward problem model photon propagation function

Forward problem model photon fluence weight functions are drawing elliptic banana shape which can be seen in **Fig.1**. Time resolved (TR), continuous wave (CW) or frequency domain (FD) photon weights all have banana shape trajectories for back-reflected DOT modality.

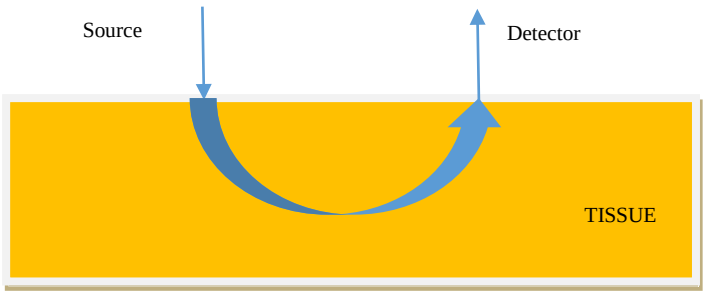



**Figure 1.** Forward problem photon propagation model

**In Fig.1**, source, detector positions and photon input and output angle directions are shown. This figure might be part of multi-source and detector matches. However, for the simplicity of explanation, single source and detector representation has been chosen. This is showing us forward problem model weight coefficients' tendencies between source and detector locations inside the imaging tissue geometry. This is not the photon fluence distributions for specific source and detector positions. This figure is showing us weight matrix coefficients between source and detector positions for back reflected geometrical structure. Differences between distributed photon fluencies and forward problem model weight matrix coefficients should be well understood by the readers, since these two concepts are totally different from each other.




**Figure 2.** Time resolved (TR) pulsed laser source photon propagation model and photon acquisition at detector position

In **Fig. 2**, single source and detector placement to back reflected tissue imaging geometry was shown. From source position, picosecond (ps) full width half-maximum (FWHM) laser is sent through imaging tissue. At the detector side, escaping photons are collected, one spike then exponentially decreasing signal is observed. Fast spike signal is connected to the superficial photon penetration, then exponential receiving signal is coming from deeper voxels.

# Method

### Monte Carlo Simulation

Monte Carlo (MC) simulation was run for specific biological tissue type in time interval (TI) mode. The ANSI standard C program generated photon fluencies for imaging tissue, successfully. The philosophy of work was about to create photon fluence distributions inside the specific tissue type. Photon fluencies were not transferred to the mathematical inverse problem solution image reconstruction algorithm platform, only time gated photon fluencies were observed and drawn for scientific illustration purpose. MC ANSI standard C run code [1] was modified and run. This program code does not include the time resolved (TR) picosecond laser pulse simulation run mode configuration. This is Continuous Wave (CW) photon propagation code for specific tissue model. However, it contains time gated photon counting program block, so deposited photon energies and fluencies are saved for different time intervals. Tissue optical parameters were selected such that absorption coefficient $\mu_a = 0$ $cm^{-1}$ (absorption coefficient was neglected), and scattering coefficient $\mu_s = 100$ $cm^{-1}$.

### Time Resolved Monte Carlo (TRMC) simulation

Time Resolved Monte Carlo (TRMC) simulation was run for cylindrical geometry. From isotropic source position, photons were beamed on to the homogeneous tissue. Time steps were chosen from 100 ps through 1000 ps, consecutively. In the results and discussion section, generated photon fluencies were shown in **Fig.3** and **Fig.4.** ANSI standard C program was run under the Cygwin platform.

# Results and Discussion

### Photon Fluencies

Specific point time gated (TG) or time resolved (TR) simulation analyses are giving us opportunity to divide imaging tissue model connected through depth analyses. Layers are divided through different depth sections. Photons can be interpreted as they are in the different cage compartments. Photon propagation in different time intervals might be different as shown in **Fig.3** and **Fig.4**. Photons can propagate up to 7 mm at time 200 ps on the other hand photons can penetrate up to 2 cm depth for the same tissue model. Researcher can make a good connection between escaping photons and time gates. This is how time resolved diffuse optic tomography (TRDOT) instrumentations are made. Picosecond (ps) solid state Titanium Sapphire (TiSa) laser can be used as a light source, and single photon counting photo-multiplier tubes (PMTs) or single photon avalanche photodiodes (SPADs) can be used as the photodetectors.

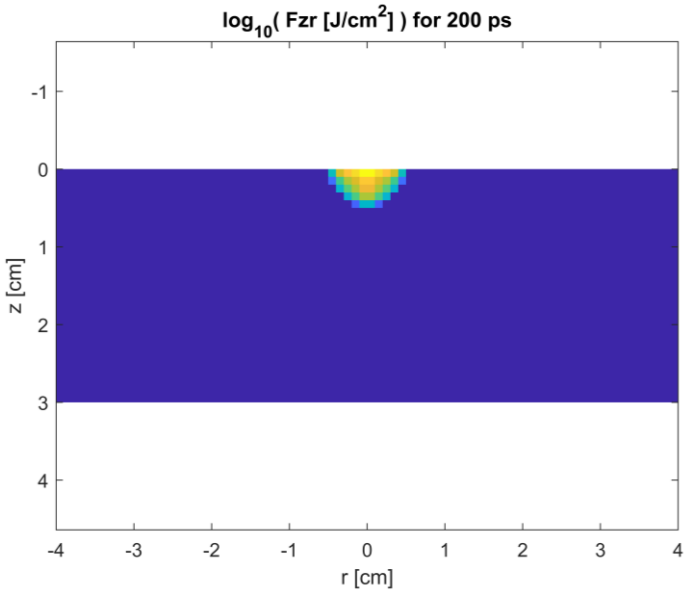



**Figure 3.** 200 ps photon fluencies

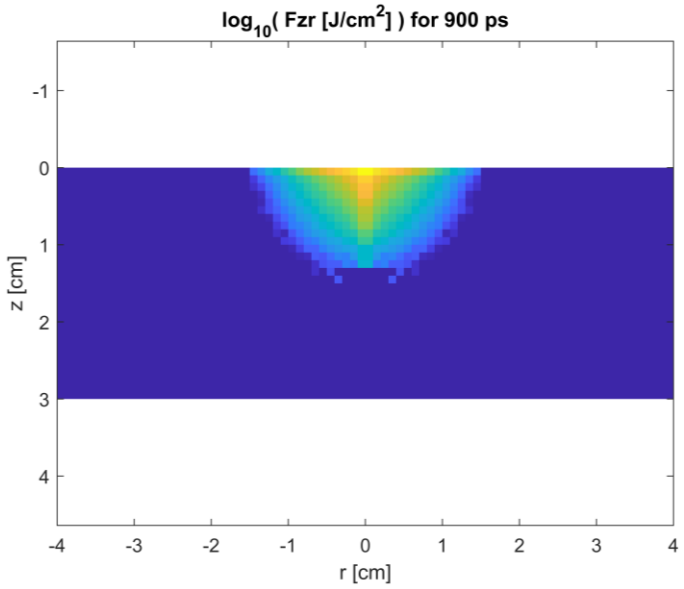



**Figure 4.** 900 ps photon fluencies

## Conclusion

Time resolved Monte Carlo (TRMC) simulation was performed to be able to analyze Continuous Wave (CW) laser photons inside the biomedical imaging tissue, successfully. Time resolved migrating photon fluencies were drawn for different discrete time gates such as 100 ps to 1000 ps, consecutively. Time varied photon fluencies were shown. Continuous wave (CW) photon distributions can be used for time resolved device instrumentation, successfully. It is not necessary to set TRDOT systems by using very expensive ps pulsed lasers such as Titanium Sapphire (TiSa) as usually mentioned in academic literature. Photo detecting device instruments are also very expensive such as single photon detecting photo-multiplier tubes (PMTs), intensified CCD and CMOS imagers. On the other hand, single photon detecting avalanche photodiodes (SPADs) as detectors and vertical cavity surface emitting lasers (VCSELs) as sources can be combined together and used for device configuration in data acquisition processes, secondly TRMC simulation program code can be run to build forward problem model, and finally mathematical inverse problem solution algorithmic methods can be applied to construct images, successfully. In this study, one alternative philosophy to generate forward problem model weights for TRDOT was represented for future works.

## Recommendations

Time resolved Monte Carlo (TRMC) simulation was run based on the photon-tissue interactions, which are scattering ($\mu_s$) and absorption ($\mu_a$) tissue optic parameter coefficients for related laser wavelength. In simulations, photons have not spin and angular momentums. In the future, spin and angular momentum of penetrating photons can be included.

## Acknowledgements or Notes

Trmc.c ANSI Standard C program source code was modified for this paper, which was originally written by Steven L. Jacques, Oregon Health & Science University (OHSU).

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